

Intermetallic and Ceramic Matrix Composites for 815 to 1370 °C (1500 to 2500 °F) Gas Turbine Engine Applications

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INTERMETALLIC AND CERAMIC MATRIX COMPOSITES FOR 815 TO 1370 °C

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Summary

Light weight and potential high temperature capability of intermetallic compounds, such as the aluminides, and structural ceramics, such as the carbides and nitrides, make these materials attractive for gas turbine engine applications. In terms of specific fuel consumption and specific thrust, revolutionary improvements over current technology are being sought by realizing the potential of these materials through their use as matrices combined with high strength, high temperature fibers. The United States along with other countries throughout the world have major research and development programs underway to characterize these composite materials; improve their reliability; identify and develop new processing techniques, new matrix compositions, and new fiber compositions; and to predict their life and failure mechanisms under engine operating conditions. This paper summarizes the status of NASA's Advanced High Temperature Engine Materials Technology Program (HITEMP) and describes the potential benefits to be gained in 21st century transport aircraft by utilizing intermetallic and ceramic matrix composite materials.

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Introduction

The U.S. aerospace industry is one of the few industries that has an acknowledged superiority over its foreign competitors both in the commercial market and as a major part of our defense industry. The aircraft industry, including the engine industry has been a net exporter, contributing positively to the balance of payments of the United States. However, in recent years, the United States' portion of this industry has been eroded due to European activities in this arena.

As we look to the future, Japan looms on the horizon as another major competitor. Their position has been strengthened in the near term by the agreement they have reached with the United States to produce the FSX fighter aircraft. But, of greater concern to researchers in the advanced intermetallic/ceramic matrix composites area is the commitment of the Japanese to high temperature composites. Already, they are the leading producers of ceramic fibers on a commercial basis. In addition, they have long-term programs underway in both intermetallics and ceramic base composites to achieve the goals that we see necessary for aircraft engines of the 21st century. With the change in emphasis by U.S. companies to unite with European and Japanese companies to coproduce aircraft engines and airframes, this international conference on "Advanced Metal & Ceramic Matrix Composites" is very timely.

Historically, nickel-base superalloys have paced the operating temperature of high-efficiency, gas turbine engines for civil transport aircraft and for high-performance, military aircraft. Evolutionary increases in use temperature of superalloys have been achieved by such developments as improved melting and processing techniques, directional solidification, single crystals, and composition optimization. It is becoming apparent, however, that the gains in use temperature from superalloy technology are reaching a limit, and to achieve future advances in engine efficiency and performance there must be a change to new types of materials.

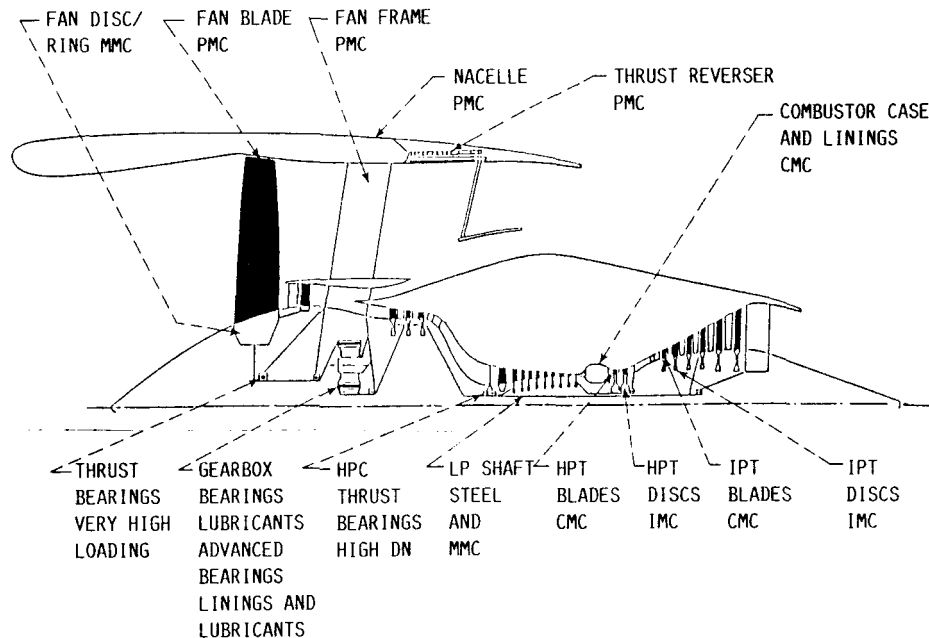
Two types of materials hold promise to not only increase the use temperature of gas turbine engines, but also hold the potential to make revolutionary gains in efficiency and performance because of their light weight. These materials are intermetallic compounds and structural ceramics. Specifically, emphasis today is primarily on the aluminides and silicon carbide and silicon nitride as matrices for advanced high temperature composites. Such efforts as the joint NASA-DOD National Aerospace Plane (NASP) program, the DOD-NASA Integrated High Performance Turbine Engine Technology (IHPTET) program, and NASA's Advanced High Temperature Engine Materials Technology Program (HITEMP) provide impetus for the understanding and development of these composite materials. This paper will summarize the efforts to date under HITEMP which has as its objective to generate technology for revolutionary advances in composite materials and structural analysis methods to enable the development of 21st century propulsion systems. Research is focused on achieving increased fuel economy, improved reliability, extended life, and reasonable costs.

Material Requirements for Future Engines

NASA Lewis Research Center is sponsoring several studies to quantify the payoffs and benefits, and to establish trade off sensitivities in future engines, if the potential of intermetallic matrix composites (IMCs) and ceramic matrix composites (CMCs) can be realized. Details of the cycles studied and engine configurations were presented at the 1st Annual HITEMP

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Review held on November 9-10, 1988 (1). One of these studies, undertaken by GE Aircraft Engines Co. (2), focuses on ultra high bypass engines (UBE) that are targeted for 747 type aircraft with a year 2015 Initial Operational Capabilities (IOC). Figure 1 shows the proposed use of advanced composites in this type of engine. It is evident that the compressor and turbine consist primarily of IMCs and CMCs along with metal matrix composites (MMCs) to be used in the low pressure (LP) shaft. The use of these materials will dictate new design approaches and new manufacturing techniques.



PMC, MMC, IMC, & CMC = Polymeric, Metal, Intermetallic, and Ceramic Matrix Composites, respectively. HPC = High Pressure Compressor, LP = Low Pressure, HPT = High Pressure Turbine, IPT = Intermediate Pressure Turbine

FIGURE 1. - ADVANCED MATERIALS APPLICATIONS FOR AN ULTRA HIGH BYPASS ENGINE.

Generalized materials properties for the turbine and shaft are shown in Figure 2. Current projected properties of CMCs look promising for the turbine, but to achieve maximum payoff from these materials, even higher goals are desirable. For the shaft, it will probably be necessary to employ more than one material in the LP drive shaft, steel to withstand high spline crushing stresses and an IMC to give the good strength/density characteristics needed for this high speed rotating component. Other components face similar material properties challenges. These two examples help to point out the complexity involved in using composites where two dissimilar materials may be used in the shaft with the accompanying problems of joining for high temperature service.

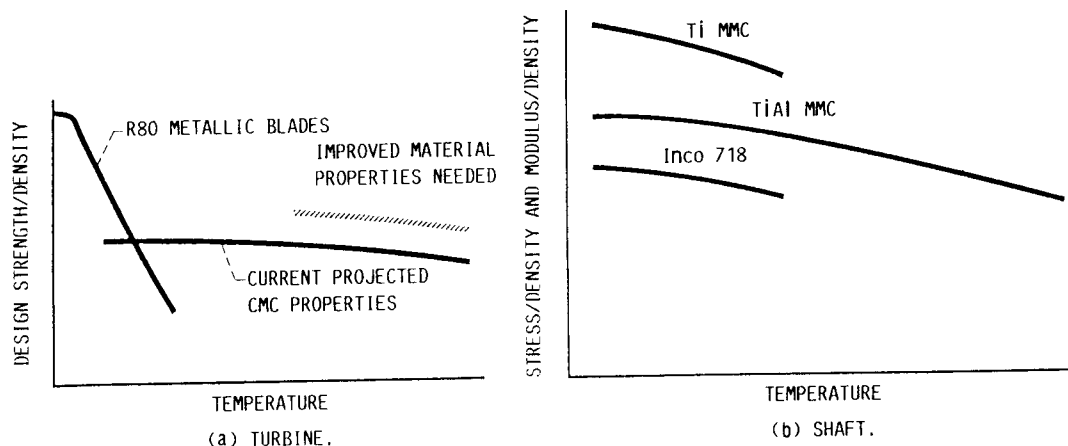


FIGURE 2. - GENERALIZED TURBINE AND SHAFT MATERIALS PROPERTIES FOR ADVANCED ULTRA HIGH BYPASS ENGINE.

A second study has been undertaken by Pratt & Whitney Engine Co. (3) to determine the materials properties required in high speed civil transport (HSCT) engines where a speed of Mach 3.2 was used as the design goal. A cross section of a preliminary design shown in Figure 3, indicates the need of IMCs and CMCs throughout the engine. Titanium and iron aluminides are called out specifically. However, as stress requirements are firmied up and temperatures finalized, the composite matrices may change.

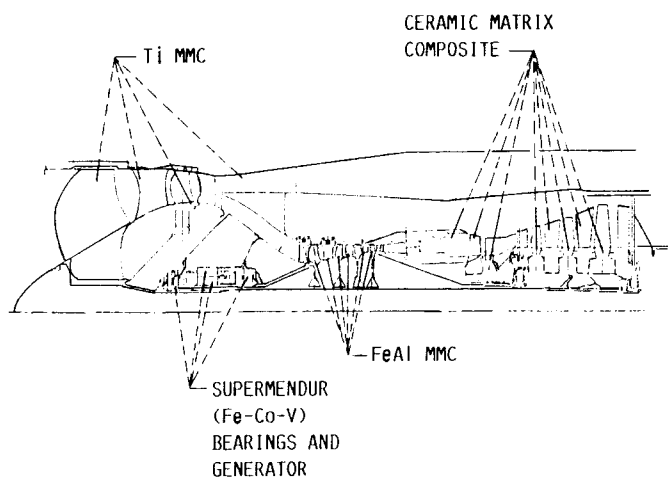


FIGURE 3. - ADVANCED MATERIALS TECHNOLOGY FOR THE HIGH SPEED CIVIL TRANSPORT ENGINE.

Some of the design concepts and fiber architecture for the fan rotor and the compressor rotor are illustrated in Figure 4. Again, joining and manufacturing technologies must be addressed in future efforts.

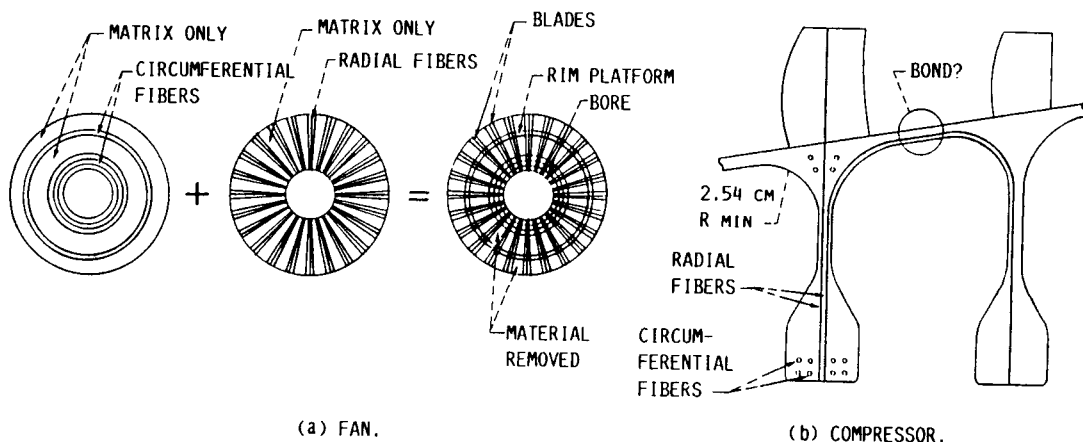


FIGURE 4. - PRELIMINARY IMC FAN ROTOR AND COMPRESSOR ROTOR CONSTRUCTION FOR A HSCT ENGINE.

IMCs - Progress/Problems/Opportunities

Intermetallic matrix composites are currently of extreme interest for future high temperature, high efficiency, high performance gas turbine engines for both civil and military applications. Some of the composites under consideration by the aerospace community with the advantages and disadvantages for those materials are summarized in Table I.

TABLE I. - SUMMARY OF INTERMETALLIC MATRIX COMPOSITES UNDER CONSIDERATION

Matrices	FeAl, Ti ₃ Al, TiAl, Ni ₃ Al, NiAl, Nb ₃ Al, NbAl ₃
Fibers	SiC, TiB ₂ , TiC, Graphite, Al ₂ O ₃
Advantages	Light weight, stiffness, design flexibility, matrix and fiber properties balanced
Disadvantages	CTE mismatch, chemical compatibility, fabrication, joining

By going the composite route, the low density of the intermetallic compounds can be utilized to good advantage and if low density, high strength fibers are available, the low strength of intermetallic matrices becomes less of an issue. Thus, the matrix can be optimized for other properties, most importantly ductility, oxidation resistance, and density. The influence of the fiber on strength properties of a composite has been discussed by McDanel's and Stephens (4) for the use of SiC in aluminide matrices where the predicted strength-to-density for SiC reinforced aluminide composites was shown to be essentially independent of matrix strength. An example of experimental results of this concept is illustrated by the results of Brindley (5). The tensile behavior is shown in Figure 5 to achieve predicted rule of mixture behavior. And on a density corrected basis, the composite is shown to have superior tensile properties compared to wrought nickel base and cobalt base alloys and a single crystal superalloy, NASAIR 100.

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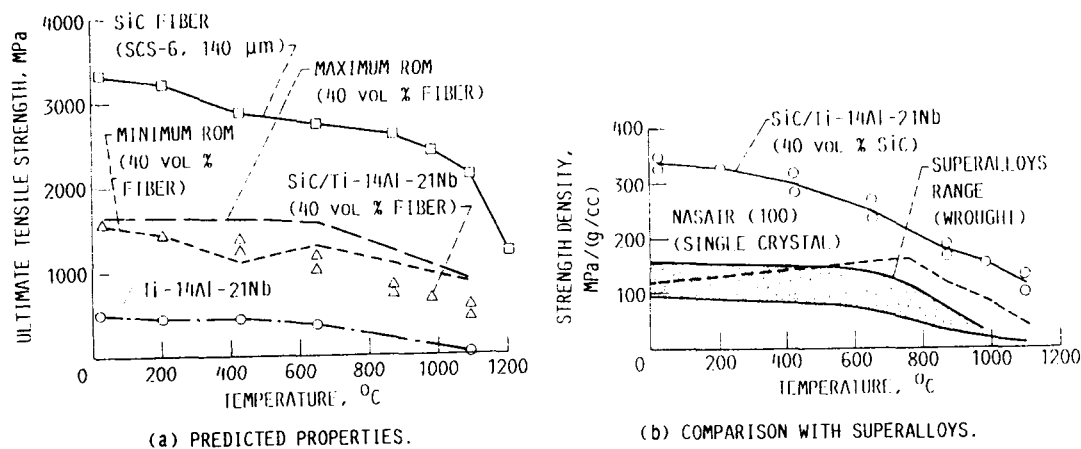


FIGURE 5. - TENSILE PROPERTIES OF A SiC/Ti₃Al+Nb COMPOSITE.

One of the major problems facing the successful development of IMCs is the compatibility between fiber and matrix both from a chemical viewpoint and the mismatch in coefficient of thermal expansion (CTE). An example of the extreme complexity of fiber matrix interaction is shown schematically in Figure 6 for a SCS-6 fiber in a Ti₃Al+Nb matrix. The SiC fiber has a two-layer carbon zone on the surface which further contributes to the chemical reactions in this system. Thermal cycling can lead to the development of microcracking as illustrated in Figure 7.

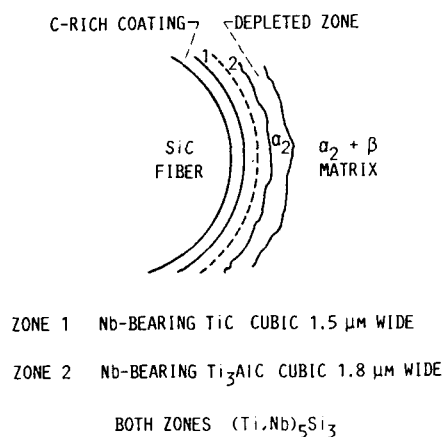


FIGURE 6. - FIBER-MATRIX REACTION ZONES.

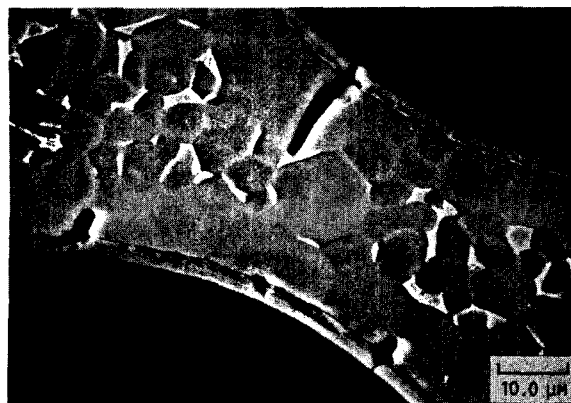


FIGURE 7. - THERMAL CYCLE INDUCED CRACKS.

These problems associated with the IMCs provide challenges and opportunities for materials and structures researchers. To overcome the compatibility problems of the fibers and matrices in IMCs a thermodynamic screening study following the methodology shown in Figure 8 is underway. In addition, the kinetics of the various reaction types is under investigation to help further in the identification of fibers for the intermetallic matrices.

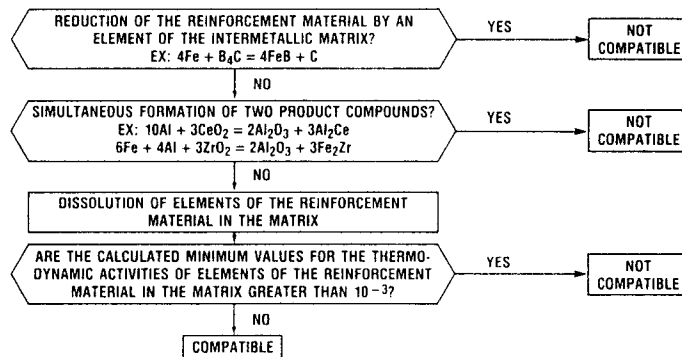


FIGURE 8. - METHODOLOGY OF CALCULATIONS TO DETERMINE THE COMPATIBILITY OF REINFORCEMENTS IN A MATRIX.

Analytical modeling is underway Ghosn and Lerch (6) to address the fiber-matrix CTE mismatch. The importance of fibers will be discussed further under the fiber section.

CMCs - Progress/Problems/Opportunities

The structural and environmental requirements for gas turbine engine components are most demanding in applications involving human transport. This necessitates a very highly reliable ceramic material which has served as a strong driver for the shift in current ceramic research from monolithic materials to CMCs that are primarily reinforced by long, high-performance ceramic fibers. Research at NASA Lewis Research Center as described by DiCarlo (7) has focused on CMCs with improved strength, reduced flaw sensitivity (improved fracture toughness), the ability to withstand stress overloads (i.e., fail in a noncatastrophic manner), and good property retention under service conditions.

Continuous fiber reinforced ceramic matrix composites (FRCMCs) can permit load transfer from the matrix to the fiber and if the fiber has a higher modulus than the matrix, then the initial modulus of the CMC will be greater than the monolithic matrix. A more important effect of high-modulus fibers, in addition to the gain in stiffness, is the added effect of producing matrix fracture at a greater stress than that observed in the monolithic material. Interfacial fiber-matrix bonding is one of the key parameters under investigation. FRCMCs can develop strong bonds during initial consolidation or during high temperature service. Under an applied or residual stress, the stress concentration factor on a fiber at the tip of a propagating matrix crack usually is high enough to fracture the fiber. This results in a strong material failing in a brittle manner. If weak interfacial bonding is achieved, however, fiber-matrix debonding occurs at the matrix crack tip and matrix cracks propagate around rather than through the fiber. The ideal bond will permit the fibers to bridge matrix macrocracks and the FRCMC will elongate rather than fail. Figure 9 shows an idealized stress-strain curve for fiber-matrix bonding in a FRCMC. Actual

data for silicon carbide reinforced reaction bonded silicon nitride (RBSN), Bhatt (8) are shown in Figure 10. The composite fails in a noncatastrophic manner and has matrix cracking strength and ultimate failure strain significantly higher than monolithic RBSN.

In addition, the effects of cross plying on the CMC are illustrated. Further results on the SiC/RBSN composites with properly designed interfaces withstand large transverse notches with little or no loss in strength and show no loss in tensile strength after thermal shock conditions that would seriously degrade the strength of monolithic RBSN.

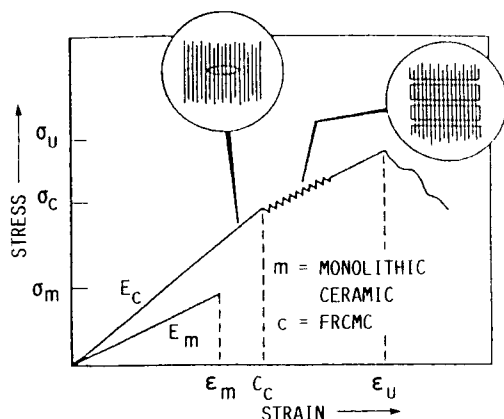


FIGURE 9. - GRACEFUL FAILURE IN CMCs (IDEALIZED).

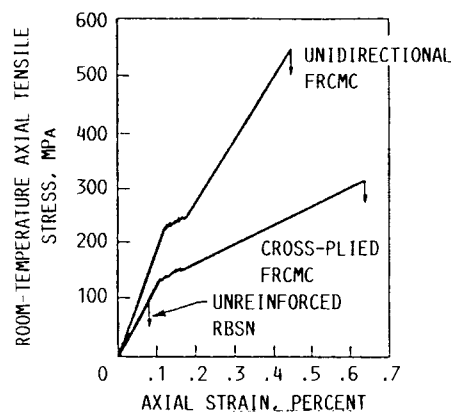


FIGURE 10. - "METAL" LIKE BEHAVIOR IN CMCs.

Advanced Fibers Hold the Key to High Temperature Composites

Based on the previous discussions, it is evident that fibers must be developed that can meet the high-temperature goals of advanced IMCs and CMCs for future aircraft engine applications. Table II summarizes some of the ideal property requirements that are desirable for the composites.

TABLE II. - IDEALIZED PROPERTIES OF FIBERS FOR
IMC AND CMC MATRICES

Coefficient of thermal expansion matching matrix
Low density
High modulus of elasticity
High melting temperature
High temperature strength
Chemically compatible with potential matrices
Good oxidation resistance
Good handleability-spoolable
Capable of mass production

In addition, it is currently thought that the fiber diameter for IMCs should be in the range of 75 to 350 μm , while for CMCs, small diameter fibers - near 10 μm , are thought to be desirable. However, more analytical modeling and verification testing is needed in this area before optimum fiber diameters and cross-sectional shapes (round, elliptical, irregular, etc.) can be specified.

All of these idealized properties are not available in the current, limited number of fibers available for the matrices of interest. As an alternative route, emphasis is being placed on achieving desired mechanical properties in the fiber and turning to an intermediate layer between the fiber and matrix to account for lack of chemical compatibility, mismatch in coefficient of thermal expansions, and improper bonding.

NASA is proposing to spear head an effort to develop advanced fibers that more closely meet the properties listed in Table II. This proposed 5 year effort will emphasize fiber screening for CTE and chemical compatibility, fundamentals of fiber processing, fiber characterization and evaluation, and fiber production feasibility followed by transfer of the technology to industry.

Concluding Remarks

The aircraft engine industry is facing a highly competitive future as we approach the 21st century. Materials development holds the key for the U.S. to maintain or even increase its share of the world engine market. One of the major contributors to this goal is the development of advanced intermetallic and ceramic matrix composites for engines that will be used as the propulsion systems for subsonic as well as high speed aircraft. For the materials engineers, structural analysts, and designers, tremendous challenges and opportunities should make the next decade an exciting time to be involved in this research and development field.

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